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The Effects of Steel Profile and Cleanliness on Coating Performance

ABSTRACT A 5-year study was conducted in cooperation with the Steel Structures Painting Council to determine surface profile and cleanliness requirements for long-term performance of generic coating systems currently used on Navy shore facilities. Replicate sets of the different variations were exposed in a salt fog chamber and at test exposure sites in a tropical marine atmospheric environment, in an industrial environment, and in a mild marine atmospheric environment. After 15 months of exposure at Kwajalein, little change had occurred in the overall bonding strengths of the test panels; however, in the next 42 months, a significant overall loss in bonding strength occurred. Significantly different variations occurred between the different coating systems, and the range of values was greatly reduced. Salt fog exposure had a much greater effect on loss of adhesion than did natural exposure for 57 months for the periods measured. Levels of statistical significance for performance at Kwajalein varied greatly with time and were much greater on scribed than unscribed specimens. Coating system was the most significant variable, followed by abrasive and profile height, and lastly by level of cleaning. Thus, profile was more important than cleanliness in field performance as well as in the laboratory salt fog testing and the adhesion study.

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME, CALIFORNIA 93043

METRIC CONVERSION FACTORS

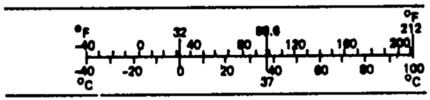
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13 10 286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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A 5-year study was conducted in cooperation with the Steel Structures Painting Council (SSPC) to determine surface profile and cleanliness requirements for long-term performance of generic coating systems currently used on Navy shore facilities. The experimental design included two levels of cleaning (white metal finish and commercial finish), four levels of profile height (low, medium, high, and very high), eight levels of abrasive (eight different abrasives), and six levels of generic coating system (alkyd, acrylic latex, vinyl, epoxy, coal tar epoxy, and

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20 Continued

inorganic zinc/vinyl) Replicate sets of the fferent variations were exposed in a salt fog chamber and at test exposure sites in a tropical marine atmospheric environment at Kwajalein Atoll in the Marshall Islands, in an industrial environment at Pittsburgh, Pa , and in a relatively mild marine atmospheric environment at Kure Beach, N C. After 15 months of exposure at Kwajalein, relatively little change had occurred in the overall bonding strengths of the test panels, however, in the next 42 months, a significant overall loss in bonding strength occurred Significantly different variations occurred between the different coating systems, and the range of values was greatly reduced. Salt fog exposure had a much greater effect on loss of adhesion than did natural exposure for 57 months for the periods measured Levels of statistical significance for performance at Kwajalein varied greatly with time and were much greater on scribed than unscribed specimens. Coating system was the most significant variable, followed by abrasive and profile height, and lastly by level of cleaning. Thus, profile was more important than cleanliness in field performance as well as in the laboratory salt fog testing and the adhesion study

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A 5-year study was conducted in cooperation with the Steel Structures Painting Council (SSPC) to determine surface profile and cleanliness requirements for long-term performance of generic coating systems currently used on Navy shore facilities. Replicate sets of the different variations were exposed in a salt fog chamber and at test exposure sites in a tropical marine atmospheric environment, in an industrial environment, and in a relatively mild marine atmospheric environment. After 15 months of exposure at Kwajalein, relatively little change had occurred in the overall bonding strengths of the test panels; however, in the next 42 months, a significant overall loss in bonding strength occurred. Significantly different variations occurred between the different coating systems, and the range of values was greatly reduced. Salt fog exposure had a much greater effect on loss of adhesion than did natural exposure for 57 months for the periods measured. Levels of statistical significance for performance at Kwajalein varied greatly with time and were much greater on scribed than unscribed specimens. Coating system was the most significant variable, followed by abrasive and profile height, and lastly by level of cleaning. Thus, profile was more important than cleanliness in field performance as well as in the laboratory salt fog testing and the adhesion study.

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INTRODUCTION

Inadequate surface preparation is probably the most frequently reported cause of early paint failure on steel surfaces. Because of numerous early failures at Navy field activities, the Naval Civil Engineering Laboratory (NCEL) prepared a techdata sheet (Ref 1) on this subject to reduce the number of these failures. The present work was directed at developing necessary surface preparation criteria that would further insure the successful performance of coatings on steel surfaces. This report describes the results of this extensive 5-year study.

BACKGROUND

Abrasive blasting of steel is generally the preferred method of preparing steel surfaces for painting. It not only is very effective in removing most contaminants (grease and oil usually require solvent degreasing for complete removal), but it also provides a textured surface (profile) for tight bonding of paint. Incomplete removal of such surface contaminants as grease, oil, dirt, and mildew usually results in poor paint adhesion and early peeling problems; incomplete salt removal usually accelerates osmotic blistering. Too great a surface profile will result in inadequate covering of peaks and will result in early pinpoint rusting, while too low a profile may not permit adequate bonding.

Different generic types of paint (paints are classified according to the generic type of their binders) require different levels of cleanliness and profile. Thus, it is rather well-accepted that drying oil paints, such as alkyds, are relatively tolerant of incompletely prepared surfaces, and inorganic zinc paints require a very high level of cleanliness. The preferred steel surface profile may be related to the thickness of the primer being applied, the total surface area, or the general profile shape. A profile height half the dry film thickness of the primer but never more than 2-1/2 mils is frequently recommended. Thus, a 2-1/2-mil profile height would be appropriate rather than 5 mils when a thick 10-mil coat of primer is to be applied. Coating thickness is related to formulation and generic type. The desired blast profile height is usually achieved by selecting a particular abrasive and the dwell time.

Abrasives of sand, shot, and grit are used in blast cleaning steel prior to painting. Each specific abrasive provides a different profile height as well as shape. Softer abrasives break down more during blasting than harder abrasives to leave greater amounts of residue on the cleaned surface; all residues require removal by blowing air, brushing, or vacuuming before painting the surface. The size and shape of the abrasive particles greatly affect the surface texture. Thus, relatively large and rounded shot provides a flat, shallow profile, while angular grit provides a more jagged profile.

From the above discussion, it is apparent that many factors are important in both defining criteria for the necessary surface preparation of steel for lasting coating performance and in achieving these conditions. This investigation was conducted to develop some of these criteria.

EXPERIMENTAL DESIGN

The test design of this investigation was an analysis of those variants in surface preparation that were considered to be important in achieving good adhesion of a primer to steel and good protection of the metal by the total coating system. Such a design would be effective in detecting interactions of variants, as were expected to occur. Structural steel panels, 1/4- by 4- by 12-inch, were blasted with abrasives (hereinafter referred to as "abrasive blasted") to a white metal finish (Steel Structures Painting Council (SSPC) SP 5) using conventional blasting equipment. Eight different abrasives were used. The profile heights that resulted are as follows:

Abrasive	Profile Height
Steelgrit G-14	Very high
Steelgrit G-40	Medium
Polygrit 40	Medium
Polygrit 80	Low
Black Beauty 400	Medium
Black Beauty 4016	High
Flint Shot	Low
Steel Shot S280	Medium

In addition, two of these abrasives (Black Beauty 4016 and Polygrit 40) were used to clean panel surfaces to a commercial finish (SSPC-SP 6) to give a total of 10 surface variations.

Six coating systems were chosen for the investigation:

System Number	System Description
1	Alkyd System: Two coats of TT-P-86 Type III primer and one finish coat of SSPC-Paint 104.
2	Acrylic Latex System: Three coats of SSPS-Paint XWB1X.
3	Vinyl System: One coat of SSPC-PT 3 Wash Primer, two coats of MIL-P-15929, and one coat of SSPC-Paint 9.
4	Epoxy: One coat of SSPC-Paint XEP1X, one coat of SSPC-Paint XEP2X, and one coat of SSPC-Paint XEP3X.
5	Coat Tar Epoxy: Two coats of SSPC-Paint 16.
6	Inorganic Zinc/Vinyl (Zinc-Rich): One coat of SSPC-Paint XZ1X, one coat of SSPC-PT 3 Tie Coat, and one coat of SSPC-Paint 9.

These systems were chosen because the[illegible] [illegible]esent different generic types that are widely used in the Naval Shore [illegible]lishment. It was not intended that conclu-ions be made about the relative performances of each of these coatings except as they were related to the surface preparation variables. Each coating system was spray applied to each of the 10 surface variations. Thus, each complete set of test panels totaled 60. Average dry film thicknesses of the coating systems on the test panels are listed in Table 1. Two 2-inch-long cuts were made in the form of an "X" in the lower one-third of each coated panel. This exposed the steel substrate so that such effects as undercutting at breaks in the coating film could be measured.

The preparation of the test specimens (surface preparation and coating application) was contracted to SSPC. SSPC became enthused over the possibilities of obtaining additional important information by expansion of the program. Thus, in addition to preparing specimens for the NCEL adhesion testing and performance study at Kwajalein Atoll in the Marshall Islands (the NCEL test site for rapid natural acceleration), SSPC prepared for itself additional sets of panels for studies of the uncoated surfaces, laboratory salt fog exposure, and field exposures in an industrial site at Pittsburgh, Pa., and a milder marine exposure at Kure Beach, N.C. (Ref 2). If a coating provides 5 years of protection at Kwajalein, it can be expected to perform well in all environments. Because the rates of coating failure at Kwajalein were much faster than at the two locations, only the results from Kwajalein were available for use in this report. This completes the NCEL portion of the work; SSPC will report their portion of the work upon its completion.

EXPERIMENTAL PROCEDURES

The bonding strengths of the 6 coating systems to the 10 different steel surfaces were determined on unexposed panels, panels exposed for 8,336 hours in a salt fog environment (SSPC used procedure 6061 of Federal Test Method Standard No. 141), and two specimens after 15 and 57 months of exposure at Kwajalein. In the procedure for determining bonding strength, steel probes were bonded to the finish coats with an epoxy adhesive (Hysol EA9309). The circular probe ends, 1 cm^2 in area, were abrasive blasted to a white metal finish before bonding. After 3 days curing, the probes were pulled in tension at a rate of 0.5 cm/min in a table model Instron testing machine until failure occurred. The coating surrounding the bonded probes was routinely cut to the bare metal before testing, even though preliminary experimentation showed that this had little effect on the measurements. Both the magnitude and the type of failure were recorded. Breaking strengths were recorded to the nearest 0.5 kg/cm^2. Performance at Kwajalein was rated using the American Society for Testing and Materials (ASTM) rating systems found in the Annual Book of ASTM Standards. A weighted rating was used to rate "general protection." In all cases, a general protection rating of 10 indicates no degradation, and a rating of 7 indicates failure. No panels were examined further after receiving a rating of 7.

DISCUSSION OF EXPERIMENTAL RESULTS

In this section, adhesion and performance data after natural exposure are presented. A summary of previously reported data on initial adhesion and accelerated salt fog testing are added in appropriate locations to give a total picture of the work undertaken and to permit additional comparisons.

Adhesion Tests

The changes that occurred in bonding strengths at various time intervals are shown in Table 2 for each of the six coating systems. Before any exposure, the bonding strengths varied from 22 to 180 kg/cm^2. After 15 months of tropical exposure at Kwajalein, two very significant changes had occurred. The bonding strengths of the coal tar epoxy specimens had greatly decreased, and the bonding strengths of the acrylic latex specimens had greatly increased. The latter was probably from loss of surfactant. The bonding strength of the zinc-rich system had also increased very slightly. After 57 months, all bonding strengths had dropped from the 15-month ratings except for the zinc-rich specimens, which had further increased slightly. The bonding strength of the acrylic system had dropped only slightly and was now the greatest of all the coating systems. The average of the bonding strengths after 8,383 hours of laboratory salt fog exposure was lower than the average of the bonding strengths after 57 months of tropical exposure.

In Table 3, the average bonding strengths measured after various time intervals are tabulated for each abrasive used. The range was much less than that for the individual coating systems in Table 2. The combined average had not changed after 15 months but dropped from 93 to 55 kg/cm^2 after 57 months. As expected, there was a great variation in the extent to which the bonding strengths associated with the different abrasives varied with time, and only very slight increases were noted in the bonding strengths after 15 months and none after 57 months of natural exposure. Again, the average bonding strengths after 8,336 hours of laboratory salt fog exposure were lower than those from specimens after 57 months of tropical exposure.

When the average bonding strengths associated with different profile heights were tabulated, small ranges like those with the abrasive were obtained. This was true to even a greater extent when level of cleaning was considered.

In an earlier report of initial adhesion studies (Ref 2), the following significant variables were found to be related to initial adhesion:

Variable	Level of Significance
Coating Type	0.999
Abrasive	0.999
Coating Type-Abrasive Interaction	0.999
Profile Height	0.999
Coating Type-Profile Height Interaction	0.999
Cleaning Level	0.90
Coating Type-Cleaning Level Interaction	0.90

These data can be summarized as follows:

1. Initial adhesion was quite different with different coating systems.

2. Initial adhesion was quite different with different abrasives.

3. Some coating systems had much better initial adhesion with one or more specific abrasives than with others.

4. Initial coating adhesion was quite different with different profile heights.

5. Some coating systems had better initial adhesion with one or more profile heights than with others.

6. Initial adhesion was slightly better on steel blasted to a white metal finish than to a commercial finish.

7. The greater cleanliness level (white metal finish) was more important to some coating systems than to others in promoting adhesion.

Exposure Tests

There are many ways to statistically analyze the performance data received. An attempt was made to find and present the most meaningful conclusions in a simple but adequate manner. Because there were very significant rating differences between scribed and unscribed areas, these areas were rated and statistically analyzed separately. Also, all the analyses presented here are for general protection, rather than some of the individual items that comprise that rating, since these data are believed to provide the most meaningful conclusions. Other data are currently being analyzed in a study of the mechanisms of coating deterioration.

Analysis of Coating Systems, Abrasives, and Their Interaction. Tables 4 and 5 show the levels of significance of coating systems, abrasives, and their interaction over the 54-month rating period for scribed and unscribed areas, respectively. It can be seen from these and later tables that the levels of significance varied greatly over the 54 months. Also, levels of significance are much greater for the scribed than the unscribed areas. Thus, in the scribed areas, the three variables have a high level of significance, while in the unscribed areas, only the coating system has a consistently high level of significance. To put it more directly, there were greater variations in performance in the scribed than the unscribed areas. Although it was not intended that conclusions should be made about the overall performance of one generic type of coating as compared to another, summaries of their performances on scribed and unscribed panels are presented in Tables 6 and 7, respectively, to show rates of deterioration, differences in performance in scribed and unscribed areas, and changes in the order

of ranking over the rating period. While the epoxy system always ranked first or second in both scribed and unscribed areas, the zinc-rich system performed well only in the scribed areas. This is consistent with the ability of the zinc-rich primer to provide cathodic protection to the underlying steel only at areas where the barrier topcoat has been damaged. It should be noted that the zinc-rich system was different from the others in that it performed better in the scribed areas than unscribed areas after 18 months of exposure. It can also be seen that the acrylic latex and vinyl systems generally ranked two positions higher in the unscribed than the scribed areas. This is, of course, partly due to the lower ranking of the zinc-rich system in the unscribed areas. A summary of the ratings on scribed panels in relation to the abrasive used is shown in Table 8. It can be seen from this table, as well as the lower levels of significance in Table 4, that rating variations between different abrasives were relatively small.

The following observations were made from the general protection data in the scribed areas concerning the interaction of the coating systems and the abrasives:

1. The zinc-rich system had the highest ratings of all the systems except when Polygrit 80 was used as the abrasive.

2. The alkyd system rated the lowest with all abrasives.

3. The acrylic latex system rated especially low when Black Beauty 400 was the abrasive.

4. The epoxy system rated above average with all abrasives except Steelgrit G-40 and Steel Shot.

5. The vinyl system rated above average when Steelgrit G-14, Polygrit 80, and Black Beauty 4016 were the abrasives.

6. Black Beauty 4016 rated very high with the epoxy, vinyl, and zinc-rich systems.

7. Steelgrit G-40 rated very low with all except the zinc-rich system.

The following observations were made from the general protection data in the unscribed areas concerning the interaction of the coating systems and the abrasives:

1. The epoxy and the vinyl systems rated highest and the alkyd system lowest when all abrasives were considered.

2. The zinc-rich system rated very low with all abrasives except Black Beauty 400 and Black Beauty 4016.

3. The coal tar epoxy system rated very high when Polygrit 80 and Polygrit 40 were the abrasives.

4. The acrylic latex system rated high only when Steel Shot was the abrasive and rated especially low when Black Beauty 400 was the abrasive. The Steel Shot may have provided a very favorable profile shape.

5. Steelgrit G-14 and Flint Shot rated the highest of all the abrasives when all coating systems were considered.

Obviously, the effect of the variable abrasive may be related to contamination of the surface with abrasive residue, as well as to the profile generated. The magnitude of effects of such contamination has not been established.

Analysis of Coating Systems, Profile Heights, and Their Interaction. Tables 9 and 10 show the levels of significance of coating systems, profile heights, and their interaction for scribed and unscribed areas, respectively, at various times during the 54-month rating period. Again, it can be seen that rating variations and thus significance are much greater for the coating system than the other two variables. The differences in level of significance of coating systems in these tables and in Tables 7 and 8 arise because only specimens prepared with four abrasives corresponding to the four profile heights were used in this statistical analysis, while all exposed panels were used in the previously described analyses. The profile and interaction levels of significance in Tables 9 and 10 parallel those for abrasive and its interaction with coating system in Tables 6 and 7 in being much greater with the scribed than the unscribed areas. This parallelism seems logical since the profile heights are directly related to the abrasives. It can be seen from Table 11 that the order of ranking in the scribed area was usually high, low, very high, medium. The unusual order suggests that there is at least one other factor, such as total surface area or profile shape, that is a significant factor in addition to profile height.

The following observations were made from general protection data in the scribed areas concerning the interaction of coating systems and profile heights:

1. The zinc-rich system rated highest for all profiles.

2. The alkyd, coal tar epoxy, and acrylic latex systems rated low for all profiles.

3. The epoxy, vinyl, and acrylic latex systems rated highest for high profiles.

4. The epoxy and zinc-rich systems rated second highest for low profile.

The following observations were made from general protection data in the unscribed areas concerning the interaction of coating systems and profile heights:

1. The epoxy and vinyl systems rated highest for all profiles, with the vinyl system the highest overall.

2. The alkyd system rated the lowest for all profiles.

3. The coal tar epoxy system performed best with a low profile.

4. The acrylic latex system rated high on all profiles except for high profile on which it rated low. This is consistent with its especially good performance on unscribed areas with Steel Shot.

5. The zinc-rich system performed best on a high profile and worst on a low profile.

6. A high profile gave the best results with the alkyd and zinc-rich systems.

7. A low profile gave the best results with the coal tar epoxy, epoxy, and acrylic latex systems.

8. A very high profile gave the best results with the vinyl system.

Analysis of Coating Systems, Abrasives, Cleaning Levels, and Their Interactions. A statistical analysis was made using performance data for scribed and unscribed areas of panels cleaned to the two cleaning levels using two specific abrasives. These are summarized in Tables 12 and 13, respectively. There was no statistical significance for cleaning level in unscribed areas, but a slight to very high significance in scribed areas during the 54-month rating period. The latter is further shown in Table 14. There were no consistently significant interactions.

The following observations were made from the general protection data in scribed areas concerning the interaction of coating systems and levels of cleaning:

1. The coal tar epoxy system rated best with a commercial finish.

2. The acrylic latex, vinyl, and zinc-rich systems rated the highest with a white metal finish.

3. The alkyd and epoxy systems did not rate significantly different on a commercial and on a white metal finish.

The following observations were made from the general protection data in unscribed areas concerning the interaction of coating systems and levels of cleaning:

1. The acrylic latex system rated the highest with a commercial finish.

2. The epoxy, vinyl, and zinc-rich systems rated highest on a white metal finish.

3. The alkyd and coal tar epoxy systems did not rate significantly different on a commercial and on a white metal finish.

Salt Fog Chamber Performance. Statistical analyses of SSPC salt fog data showed that: (1) for coating systems the level of significance varied greatly with time for blistering and rusting, (2) for abrasives the level of significance was 0.99 for blistering, (3) for profile height the level of significance was 0.95 for blistering, (4) for abrasives or profile height there was no statistical significance for rusting, and (5) for cleaning level there was no statistical significance for blistering or rusting. The ranking of coating system performance from best to worst was: coal tar epoxy, vinyl, epoxy, zinc-rich, alkyd, and acrylic latex. This ranking is somewhat similar to the ranking of the unscribed areas from Kwajalein, but the results of statistical analysis of performance data had significant differences. This was probably due, in part, to a different rating system. The poorer ranking of the coal tar epoxy system in natural exposure tests and its reduced adhesion after 15 months exposure in Kwajalein are due to the adverse effects of solar radiation on coal tar epoxies. The much greater thickness of the coal tar epoxy system, as compared to the other systems, helped in its salt fog performance, but it probably also accelerated its early (15 months) loss of adhesion at Kwajalein by reducing the overall flexibility of the system. The relatively high moisture resistance (low moisture permeability) of epoxies and coal tar epoxies (Ref 3 and citations therein) also aided in the performance of these systems. The laboratory salt fog environment was especially severe on the acrylic latex specimens; they were destroyed after 1,625 hours. The alkyd specimens were destroyed after 5,175 hours, but the four other systems survived the 8,383 hour exposure.

PRESENT RECOMMENDATIONS

The exposure site at Kwajalein is much more severe than that encountered at most locations, and the exposure test had, of necessity, many limitations. Nevertheless, it seems appropriate to make some recommendations based upon the data received and from other existing published information, such as Reference 4, until additional information is received from the other exposure sites. These are summarized below:

Coating System	Blast Cleaning Level: Minimum	Optimum[a]	Abrasives for Blast Cleaning: Recommended	Not Recommended
Alkyd	commercial	near white	none special	Steelgrit G-40
Acrylic Latex	commercial	white	Steel Shot	Black Beauty 400, Steelgrit G-40
Vinyl	commercial	near white	Steelgrit G-14, Polygrit 80, Black Beauty 4016	Steelgrit G-40
Epoxy	commercial	near white	Black Beauty 4016	Steelgrit G-40, Steel Shot
Coal Tar	commercial	near white	Polygrit 80, Polygrit 40	Steelgrit G-40
Inorganic Zinc	near white	white	Black Beauty 400, Black Beauty 4016	Polygrit 80

[a]To approach best possible performance or for marine atmospheric or other severe service.

GENERAL CONCLUSIONS

1. Within the test levels used, abrasive and profile height are much more important factors in determining the extent of coating adhesion and protection than is steel surface cleanliness. As expected, the generic type of coating system was the most important factor of all. Interactions occur between these factors to a significant extent to determine actual performance.

2. Bonding strengths of coatings to steel (with some notable exceptions) tend to decrease upon prolonged exterior exposure.

3. High levels of adhesion and moisture resistance (low levels of water permeability) aid in performance of coatings on steel. Greater coating thickness adds to total water resistance, but it adversely affects flexibility, particularly if solar radiation causes rapid weathering, so that it reduces adhesion and thus performance.

4. Laboratory salt fog exposure is more severe on some generic coating systems (e.g., acrylic latex) than others when compared to the effects of natural exposure.

ACKNOWLEDGMENT

The statistical analyses were performed by Mr. I.W. Anders of NCEL.

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Table 1. Thickness of Test Coatings

Coating Primer	Average Total Dry Film Thickness (mils)		
	Primer	Intermediate	Finish Coat
Alkyd	1.6	4.0	5.4
Acrylic Latex	2.2	4.5	5.2
Vinyl	2.1	4.1	5.3
Epoxy	2.2	4.7	5.8
Coal Tar Epoxy	5.7	-	11.3
Zinc-Rich	2.8	-	4.5

Table 2. Bonding Strengths of Coating Systems on Steel Abrasive Blasted to a White Metal Finish After Various Exposures

Coating System	Average Bonding Strength (kg/cm^2) After--			
	No Exposure	8,336 Hours Salt Fog	15 Months Kwajalein	57 Months Kwajalein
Epoxy	180	37	187	68
Vinyl	109	16	105	56
Coal Tar Epoxy	98	45	61	43
Alkyd	92	a	90	47
Acrylic Latex	57	a	91	86
Zinc-Rich	22	27	27	36
Average	93	31[b]	94	56

[a] Coating completely destroyed.
[b] For panels not destroyed.

Table 3. Bonding Strengths of Coating Systems on Steel Abrasive Blasted to a White Metal Finish for Each Abrasive as Measured After Different Exposure Times

Abrasive	Average Bonding Strength (kg/cm^2) After--			
	No Exposure	8,336 Hours Salt Fog	15 Months Kwajalein	57 Months Kwajalein
Black Beauty 4016	108	27	97	56
Flint Shot	99	38	95	54
Steelgrit G-40	99	16	101	49
Steel Shot S280	92	16	104	58
Black Beauty 400	91	22	97	54
Polygrit 80	87	60	86	58
Polygrit 40	86	60	80	58
Steelgrit G-14	82	11	87	56
Average	93	31	93	55

Table 4. Levels of Significance for Coating System, Abrasive, and Their Interaction on Scribed Areas Over the Test Period

Months of Exposure	Level of Significance[a]		
	Coating System	Abrasive	Interaction
6	b	0.50	0.50
12	0.999	0.99	0.999
18	0.999	0.99	0.90
24	0.999	0.999	0.95
30	0.999	0.999	0.90
36	0.999	0.95	0.70
42	0.999	0.95	0.90
48	0.999	0.95	0.99
54	0.999	0.99	0.99

[a] 0.70 = very slightly significant
0.90 = slightly significant
0.95 = significant
0.99 = highly significant
0.999 = very highly significant

[b] Less than 0.50.

Table 5. Levels of Significance for Coating System, Abrasive, and Their Interaction on Unscribed Areas Over the Test Period

Months of Exposure	Level of Significance[a]		
	Coating System	Abrasive	Interaction
6	0.95	0.50	b
12	0.999	b	0.50
18	0.95	0.50	b
24	0.99	0.70	0.70
30	0.99	0.70	0.50
36	0.999	0.75	0.94
42	0.999	b	0.70
48	0.999	0.70	0.90
54	0.999	b	0.70

[a] 0.70 = very slightly significant
0.90 = slightly significant
0.95 = significant
0.99 = highly significant
0.999 = very highly significant

[b] Less than 0.50.

Table 6. Average General Protection Ratings of the Coating Systems on Scribed Areas Over 54 Months

Coating System	Months of Exposure								
	6	12	18	24	30	36	42	48	54
Zinc-Rich	8.8	9.1	9.0	9.0	9.0	8.9	8.7	8.4	8.2
Epoxy	9.0	8.9	8.8	8.7	8.6	8.3	8.2	8.0	8.0
Vinyl	9.0	8.8	8.6	8.5	8.5	7.9	7.8	7.6	7.5
Coal Tar Epoxy	8.6	8.2	7.9	7.7	7.5	6.9	7.1	7.1	7.1
Alkyd	9.0	8.4	7.6	7.1	7.2	6.9	7.0	7.0	7.0
Acrylic Latex	8.9	8.3	7.9	7.7	7.5	6.9	7.0	6.9	7.0

Table 7. Average General Protection Ratings of the Coating Systems on Unscribed Areas Over 54 Months

Coating System	Months of Exposure								
	6	12	18	24	30	36	42	48	54
Vinyl	9.9	9.8	9.3	9.4	9.4	9.3	9.3	9.2	9.1
Epoxy	9.9	9.6	9.4	9.4	9.4	9.2	9.1	9.1	9.1
Coal Tar Epoxy	9.8	9.3	9.0	9.0	9.0	8.8	8.8	8.7	8.5
Acrylic Latex	9.2	9.2	9.2	9.0	8.9	8.7	8.5	8.3	8.1
Zinc-Rich	9.7	9.5	8.9	8.8	8.6	8.3	8.2	7.9	7.8
Alkyd	9.8	9.4	9.1	8.8	8.4	8.3	7.9	7.8	7.5

Table 8. Average General Protection Ratings Related to Each Abrasive Measured on Scribed Areas Over 54 Months

Abrasive	Months of Exposure								
	6	12	18	24	30	36	42	48	54
Black Beauty 4016	9.0	8.8	8.7	8.7	8.5	7.8	7.9	7.8	7.8
Black Beauty 400	8.5	8.7	8.4	8.0	7.9	7.5	7.8	7.6	7.6
Polygrit 40	9.0	8.9	8.6	8.4	8.4	8.0	7.8	7.6	7.5
Polygrit 80	8.9	8.7	8.6	8.5	8.3	7.9	7.8	7.6	7.5
Flint Shot	8.9	8.6	8.3	8.2	8.1	7.5	7.6	7.5	7.5
Steelgrit G14	8.7	8.5	7.9	7.8	7.9	7.7	7.7	7.4	7.3
Steel Shot S280	8.8	8.3	7.9	7.8	7.6	7.3	7.3	7.3	7.3
Steelgrit G40	8.8	8.5	7.7	7.8	7.8	7.4	7.3	7.2	7.2

Table 9. Levels of Significance for Coating System, Profile Height, and Their Interaction on Scribed Areas Over 54 Months

Months of Exposure	Level of Significance[a]		
	Coating System	Profile Height	Interaction
6	0.999	0.70	0.99
12	0.999	0.95	0.99
18	0.999	0.999	0.50
24	0.999	0.999	0.50
30	0.999	0.95	b
36	0.999	0.50	0.70
42	0.999	0.95	0.50
48	0.999	0.95	0.90
54	0.999	0.95	0.95

[a] 0.70 = very slightly significant
0.90 = slightly significant
0.95 = significant
0.99 = highly significant
0.999 = very highly significant

[b] Less than 0.50.

Table 10. Levels of Significance for Coating System, Profile Height, and Their Interaction on Unscribed Areas Over the Rating Period

Months of Exposure	Levels of Significance[a]		
	Coating System	Profile Height	Interaction
6	0.70	0.70	0.50
12	0.95	b	0.50
18	0.70	0.50	b
24	0.95	0.70	b
30	0.999	0.70	b
36	0.999	0.70	b
42	0.99	0.50	b
48	0.999	0.50	b
54	0.999	b	0.50

[a] 0.70 = very slightly significant
0.90 = slightly significant
0.95 = significant
0.99 = highly significant
0.999 = very highly significant
[b] Less than 0.50.

Table 11. Average General Protection Ratings Related to Profile Height on Scribed Areas Over 54 Months

Profile Height	Months of Exposure								
	6	12	18	24	30	36	42	48	54
High	9.0	8.8	8.7	8.7	8.5	7.8	7.9	7.8	7.8
Low	8.9	8.6	8.3	8.2	8.1	7.5	7.6	7.5	7.5
Very High	8.7	8.5	7.9	7.8	7.9	7.7	7.7	7.4	7.3
Medium	8.8	8.5	7.7	7.8	7.8	7.4	7.3	7.2	7.2

Table 12. Levels of Significance for Coating System, Abrasive, Cleanliness, and Their Interaction on Scribed Areas Over 54 Months

[There were no interactions of any significance.]

Months of Exposure	Level of Significance[a]		
	Coating System	Abrasive	Cleanliness
6	0.50	0.70	b
12	0.999	0.50	0.99
18	0.999	0.95	0.99
24	0.999	0.95	0.999
30	0.999	0.70	0.999
36	0.99	0.50	0.90
42	0.999	0.50	0.95
48	0.999	0.70	0.90
54	0.999	0.70	0.90

[a] 0.70 = very slightly significant
0.90 = slightly significant
0.95 = significant
0.99 = highly significant
0.999 = very highly significant

[b] Less than 0.50.

Table 13. Levels of Significance for Coating System, Abrasive, Cleanliness, and Their Interaction on Unscribed Areas Over 54 Months

[There were no interactions of any significance.]

Months of Exposure	Levels of Significance[a]		
	Coating System	Abrasive	Cleanliness
6	0.70	b	b
12	0.90	0.70	b
18	0.70	b	0.50
24	0.70	b	b
30	0.70	0.90	0.70
36	0.99	b	0.50
42	0.999	b	b
48	0.999	0.50	0.50
54	0.999	b	b

[a] 0.70 = very slightly significant
0.90 = slightly significant
0.95 = significant
0.99 = highly significant
0.999 = very highly significant
[b] Less than 0.50.

Table 14. Average General Protection Ratings Related to Level of Cleaning Measured On Scribed Areas Over 54 Months

Cleaning Level	Months of Exposure								
	6	12	18	24	30	36	42	48	54
SSPS-SP 5	9.0	8.9	8.6	8.5	8.5	7.9	7.8	7.7	7.7
SSPC-SP 6	9.0	8.6	8.3	8.0	7.9	7.5	7.5	7.5	7.5

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